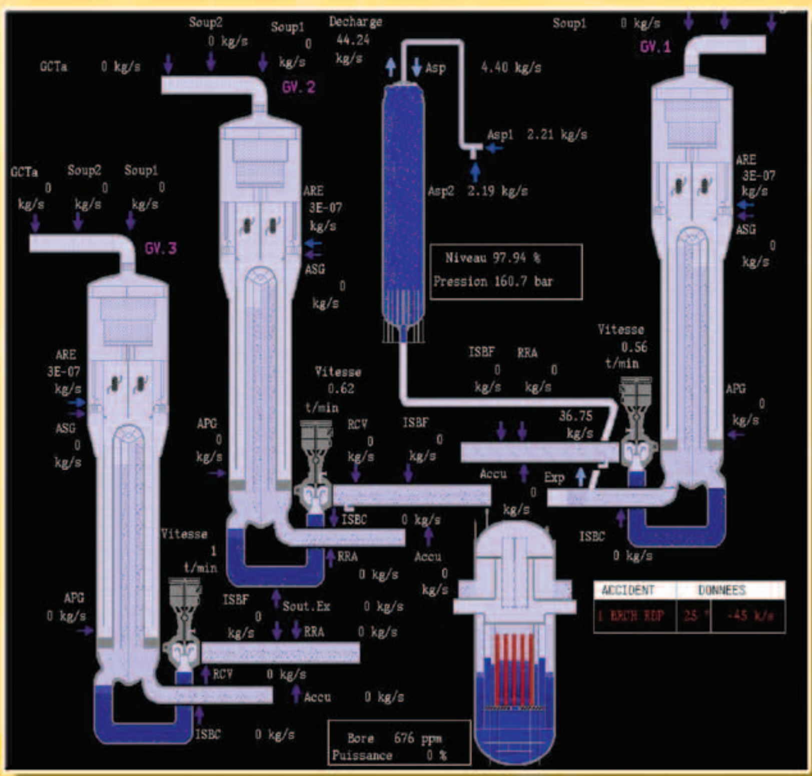
FRENCH ADVANCED SAFETY CODE FOR PWRs

CATHARE 2

CEA - EDF - FRAMATOME ANP - IRSN



CATHARE

cea

EDF Electricité de France

FRAMATOME ANP

IRSN Institut de Radioprotection et de Sûreté Nucléaire

FRAME

CATHARE 2 is the result of the joint effort of:

CEA (Commissariat à l'Energie Atomique), DEN (Nuclear Energy Division)

EDF (Electricité de France), the French utility

FRAMATOME ANP, the French vendor

IRSN (the Institute for Radiological protection and Nuclear Safety)

The CATHARE team is in charge of the code development, assessment and maintenance. It is located in Grenoble (France).

OBJECTIVES

- To develop an advanced safety code in order to perform **best-estimate** calculations of PWR accidental sequences:
  - large break LOCAs
  - small break LOCAs
  - intermediate break LOCAs
  - steam generator failures
  - other transients
- To use the code as a basis for plant simulators
- To determine uncertainties of the physical models using the assessment matrix

CATHARE APPLICATIONS

- All types of PWRs
- VVER type reactors
- Other applications:
  - boiling water reactors
  - gas-cooled reactors
  - supercritical light water reactors
  - research reactors such RJH
  - naval propulsion
  - containment thermalhydraulics
  - steam injectors
  - innovative passive systems
  - cryogenic hydraulics
  - petroleum hydraulics
  - coupling with other codes (ICARE, ISAS-SAPHIR, …)

CATHARE

MAIN OPTIONS

Needs

Extrapolation capability from the analytical tests to the reactor transients

CATHARE shall allow

- To analyse a complete set of tests covering the domain of interest for reactor safety studies
- To extrapolate interactive phenomena up to the full reactor scale
- To perform sensitivity studies

Thus, thermal non-equilibrium (critical flow, reflooding, …) and mechanical non-equilibrium (horizontal stratified countercurrent flow) have to be taken into account.

Two-fluid model

- 4 scalar equations (mass and energy)
- 2 vector equations (momentum)
- Up to 4 non-condensable gases transport equations
- Transport equations for 12 radio-chemical components

Unique set of qualified physical correlation

Modularity

SPECIFIC FEATURES

Numerics

Staggered grid and donor cell technique
First order in space and time
Fully implicit for Boundary Condition, Volume and Pipe modules
Semi-implicit for Three-dimensional module

User convenience

Pre and post-processing facilities - Flexibility

Parallel processing

Use of Open-MP model
Modular structure of the code (data and algorithms)
Allows to reach a speed-up of 5 on 8 processors for most of the reactor plant safety studies
Fully-exploited by SCAR for real-time plant simulators
Coupling of CATHARE with other codes may also be adressed using the message passing model (PVM, MPI)

CATHARE MAINTENANCE

Users' assistance

Ongoing maintenance program
Hot line for trouble shooting and advice
Workshops in French and English
CATHARE users' club meeting

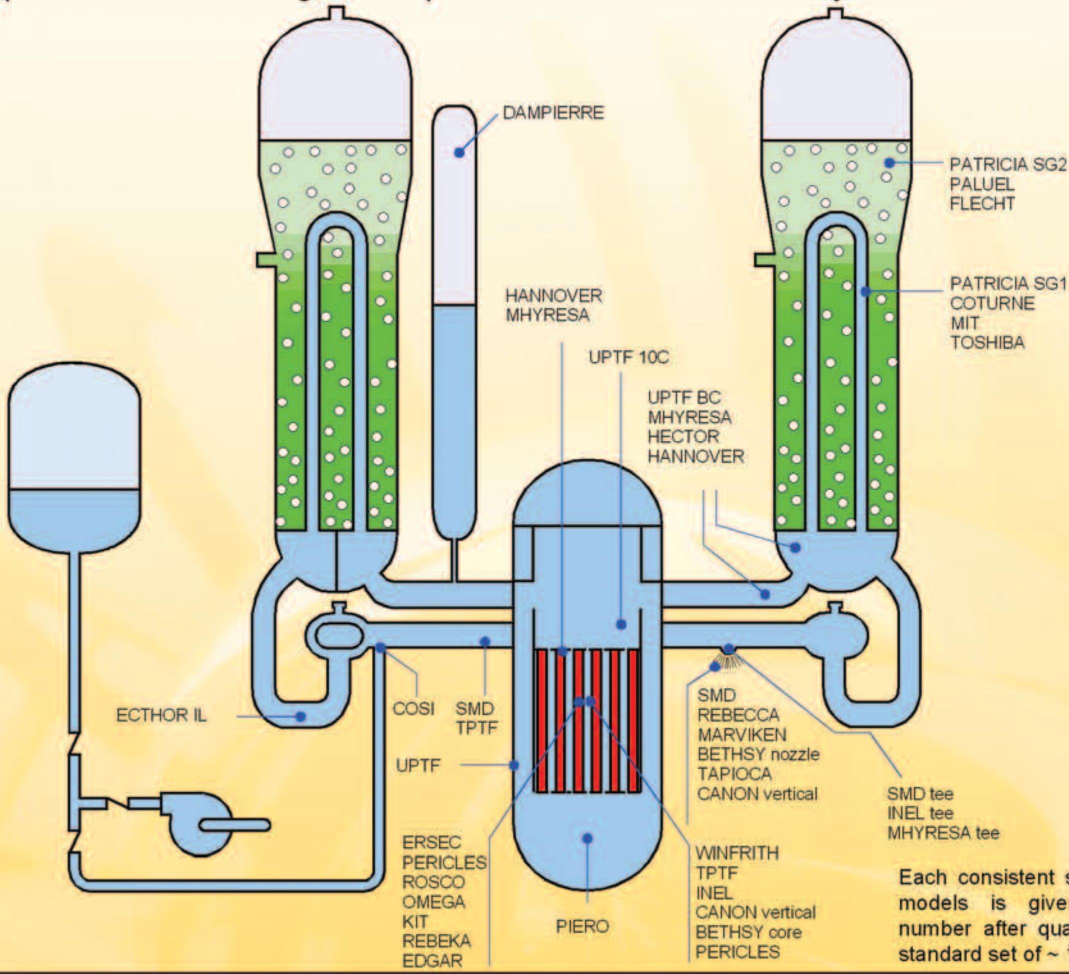
CATHARE users' club

FRANCE : CEA, EDF, FRAMATOME ANP, IRSN
EUROPE : Belgium, Bulgaria, Czech Republic, Finland, Hungary, Italy, Lithuania, Russia, Slovakia, Switzerland, Ukrainia
ASIA : China
USA : USNRC, Universities

ASSESSMENT : QUALIFICATION STEP

Qualification of physical models on separate effect tests

- Separate effect tests investigate basic phenomena involved in PWR safety studies



Each consistent set of physical models is given a revision number after qualification on a standard set of ~ 1000 tests

ASSESSMENT : VERIFICATION STEP

Verification on integral tests

- Verification of the system code consistency
- Analysis of new experiments and future systems
- Test matrix: large and small break LOCAs, natural circulation tests and other transients

BETHSY
CEA Grenoble

LOFT
INEL USA

LSTF
JAERI Japan

PACTEL
Finland

LOBI
JRC Ispra

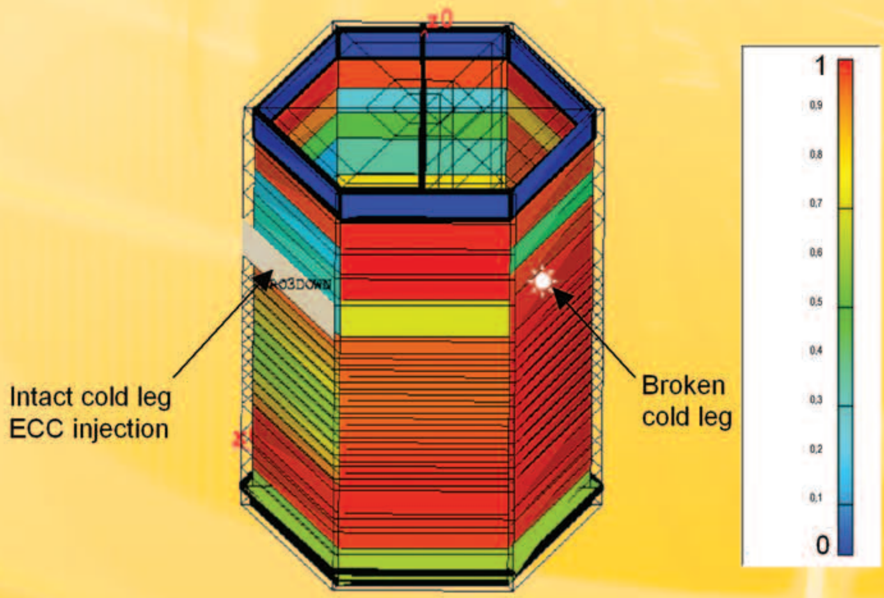
CATHARE

NEW FEATURES OF CATHARE 2 version 2.5

- ❖ Revision 6.1
- ❖ NVG point – nucleate boiling flux repartition
  Reflood (Bottom-Up and Top-Down quenching)
  Film condensation in presence of non-condensable gases
  Interfacial friction – stratified flow – horizontal pipe
  Phase distribution – tee connection
- ❖ 3-D module
  - Reactor vessel modelling
  - Reflooding model
  - Extended assessment (validation and verification)
- ❖ 4 non-condensable gases in all modules
- ❖ Transport equations for 12 radio-chemical components
- ❖ CATHARE specific application to containment transients
- ❖ New sub-modules to simulate all reactor components (valve, safety valve, ...)
- ❖ Tools for determination of physical model uncertainties
- ❖ Improved computation speed

PWR LB LOCA calculation with 3-D modelling of the vessel

- ❖ Cold leg double ended guillotine break at 100% power
- ❖ 3 loop 900 MW reactor
- ❖ 3-D meshing: 630 cells, 18 fuel sub-modules
- ❖ Total number of hydraulic nodes: 963



Partial by-pass of the sub-cooled liquid entering the downcomer from the two intact cold legs towards the broken cold leg

Void fraction in the downcomer during refilling

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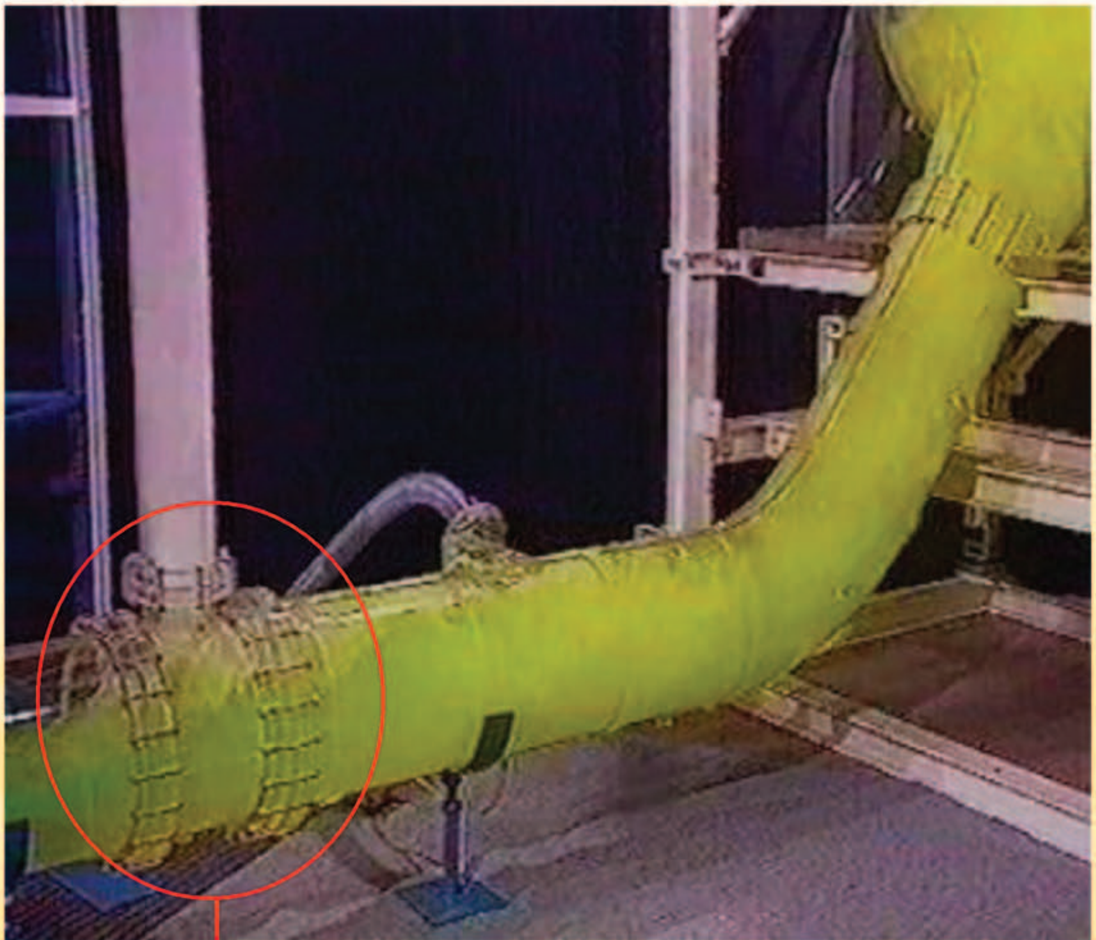
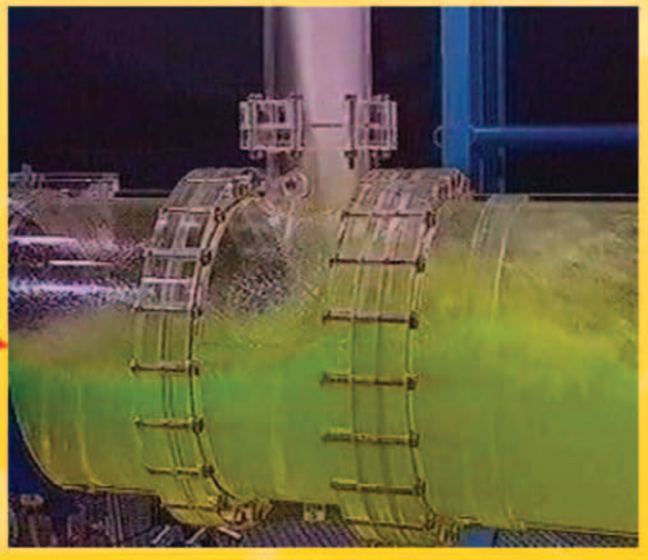
MHYRESA EXPERIMENT





CATHARE CHARACTERISTICS

Module	Models	Typical modelling applications
Basic module 1 dimension 2 fluids Fully implicit scheme	Active walls (1-D conduction model) Fuel (thermal & mechanical behaviour of a fuel pin) Reflooding (2-D heat conduction model, fine moving meshing) Thermal coupling between circuits	Hot leg Cold leg Loop seal Surge line Core channel SG riser and downcomer Steam line Vessel downcomer
Volume module 0 dimension / 2 nodes 2 sub-modules Variable separation level 2 fluids in each submodule Phase separation model	With or without active walls	Upper head Upper plenum Lower plenum SG inlet and outlet
	Specific models	Accumulator Pressurizer Steam/water separator Containment
3-D module 3 dimensions 2 fluids XYZ or RθZ meshing Nearly-implicit scheme Porous-medium approach	Active walls Fuel Reflooding	Reactor pressure vessel
BC module To impose one or more hydraulic conditions	3 types:inlet, outlet, mixed	Break, fill, dead-end, ...
Sub-modules	Source Sink Candle Break Point SG Point accumulator Valves CCFL Point pump SGTR Point kinetics for core neutronic	Injections (HPIS, LPIS) Break SG Accumulator Safety/check valve-control valve, ... Single or multiple SGTR Core

1 to 4 non-condensable gases for all modules
Transport equations for 12 radio-chemical components for all modules

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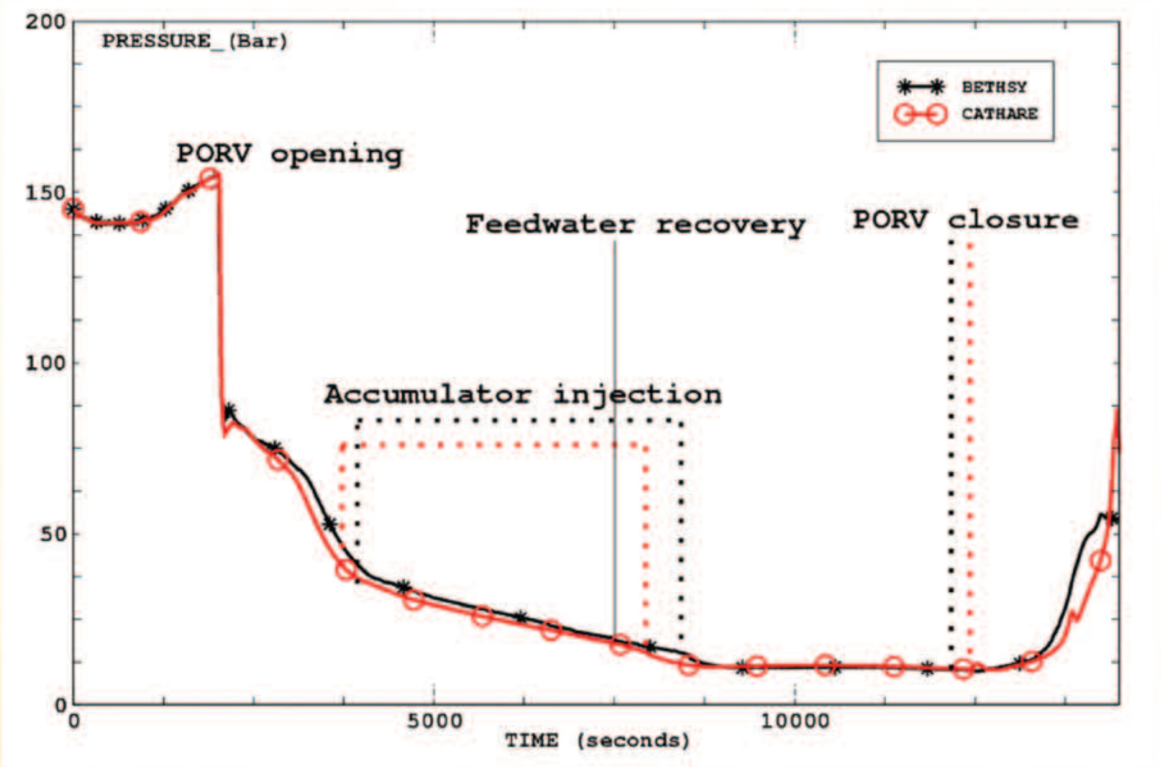
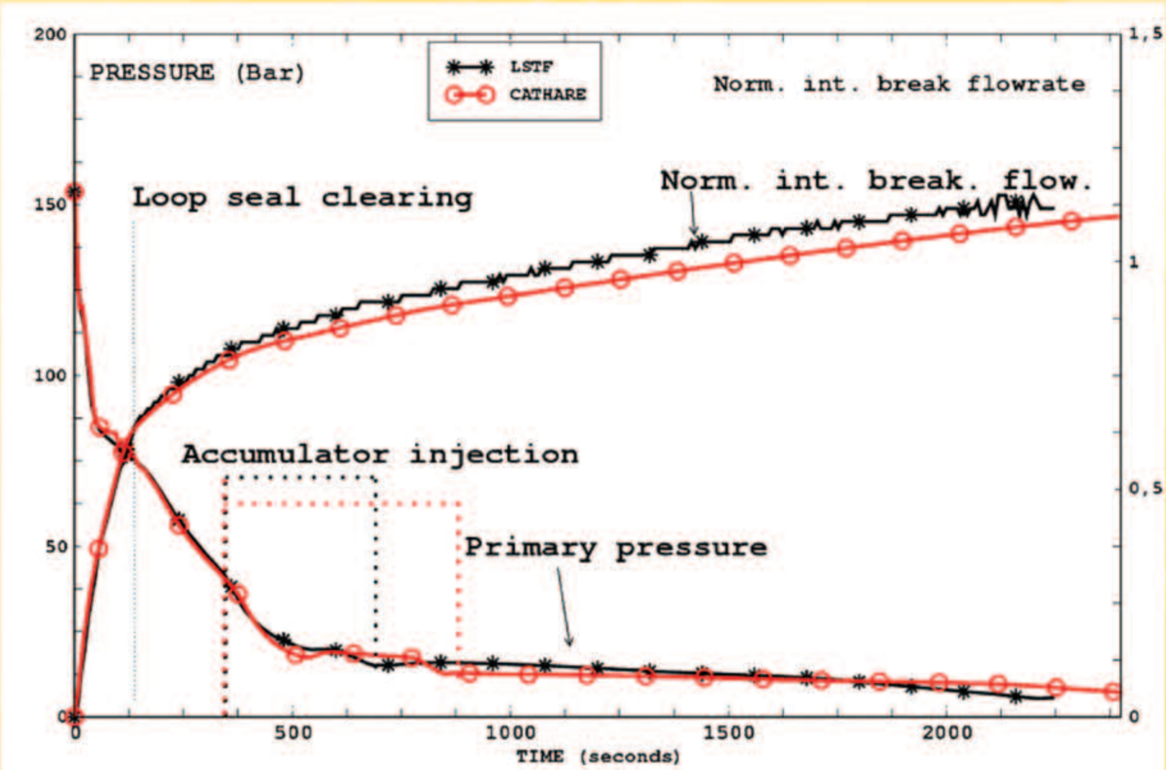
SOME RESULTS
Verification test results



BETHSY total loss of feedwater with delayed auxiliary feedwater recovery
Investigation of an emergency operating procedure (PORV opening)



LSTF 6% CL break with accumulator opening at 42 bar

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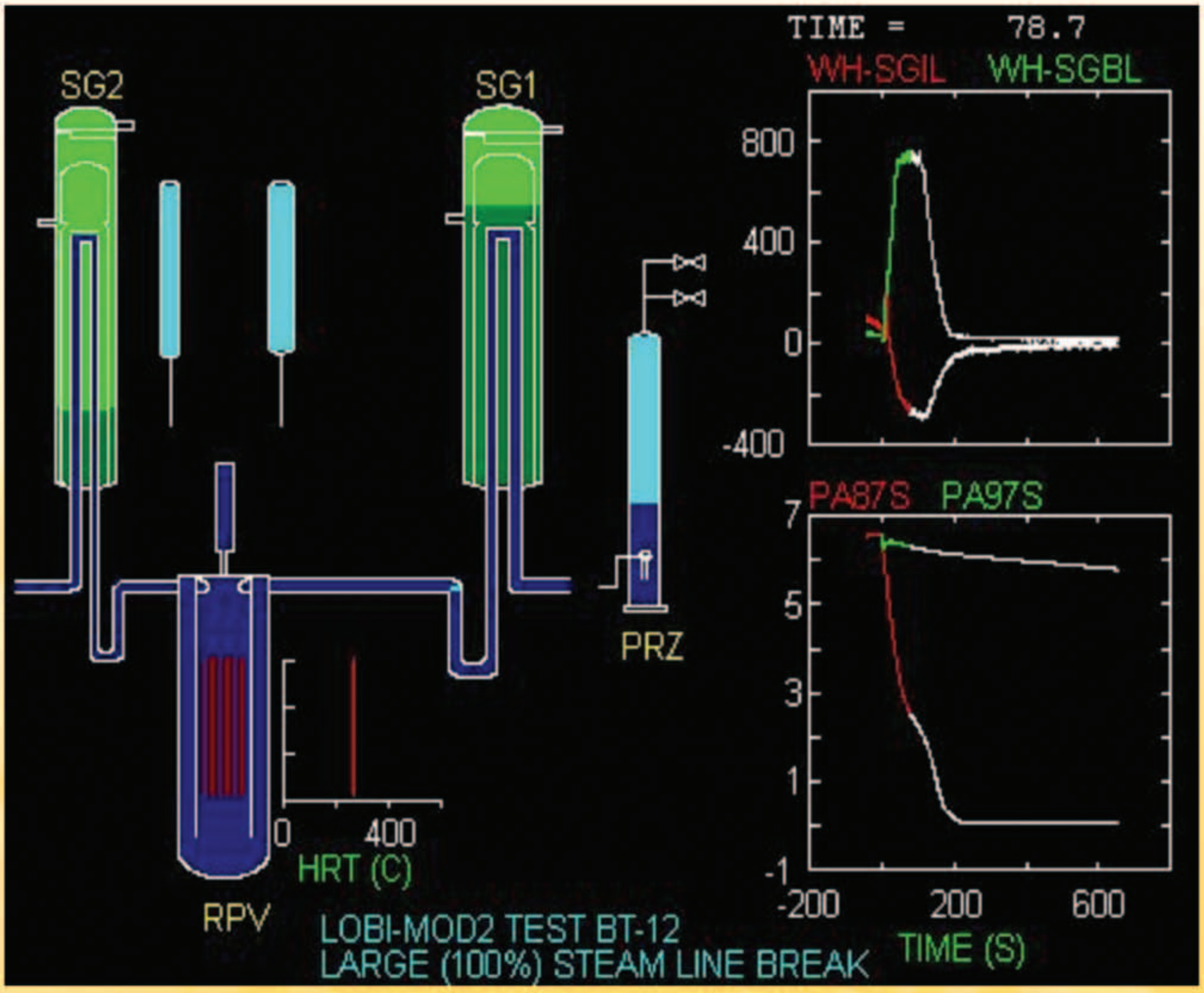
SOME RESULTS
LOBI test BT 12



Calculations performed by PISA University (Italy)

CATHARE

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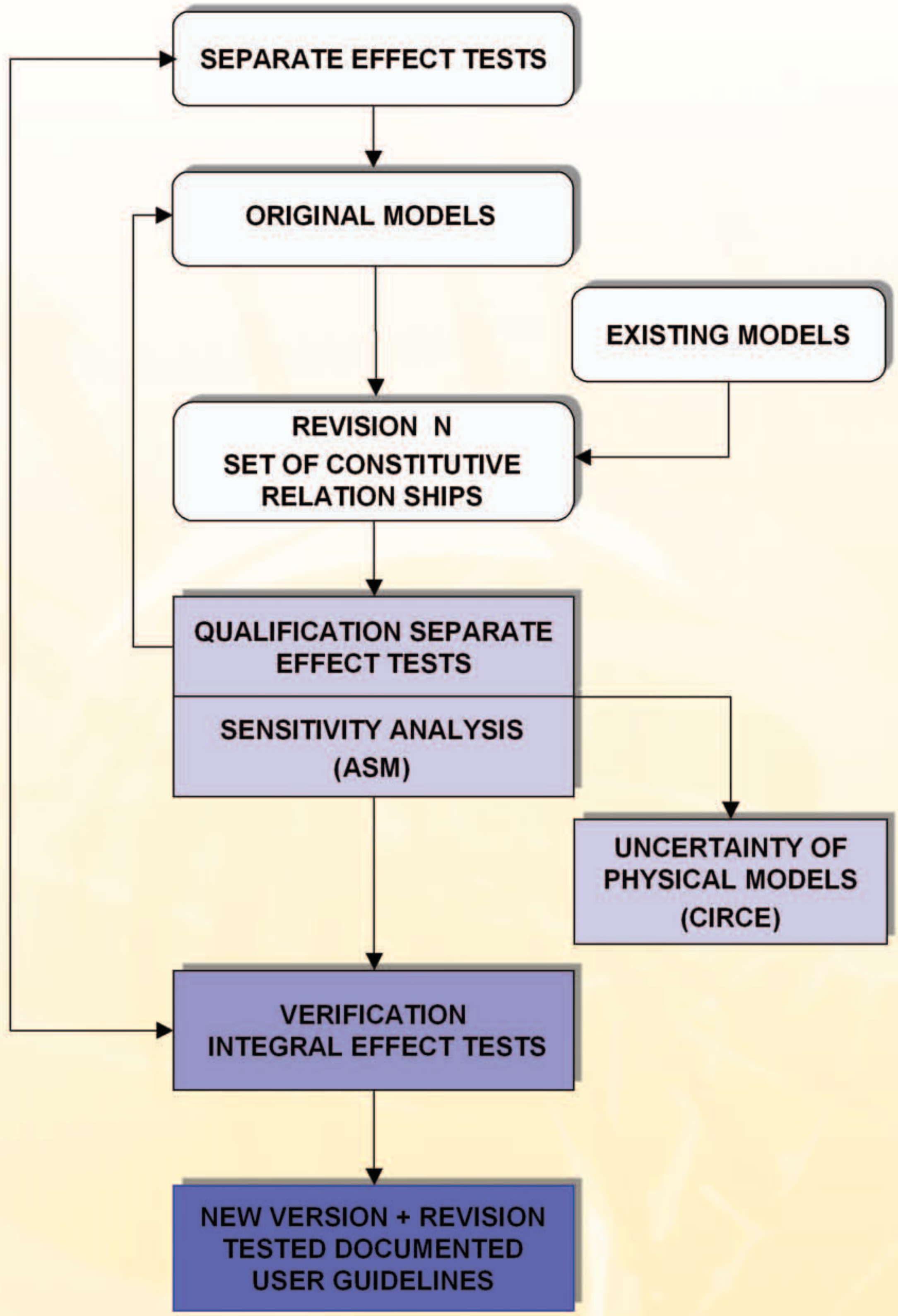
CATHARE STRATEGY



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EQUATIONS OF THE BASIC MODULE (1-D MODULE)

Mass balance equation of phase k

$$A\frac{\partial}{\partial t}\alpha_K\rho_K + \frac{\partial}{\partial z}A\alpha_K\rho_K V_K = \Gamma_{iK}$$

Transport equation for non-condensable gas

$$A\frac{\partial \alpha\rho_G X_i}{\partial t} + \frac{\partial A\alpha\rho_G X_i V_G}{\partial z} = S_i$$

Momentum balance equation of phase k

$$A\frac{\partial \alpha_K\rho_K V_K}{\partial t} + \frac{\partial A\alpha_K\rho_K V_K^2}{\partial z} + A\alpha_K\frac{\partial P}{\partial z} = AI_{iK} + \chi_f\tau_{WK} + A\alpha_K\rho_K g_Z$$

Energy balance equation of phase k

$$A\frac{\partial}{\partial t}\alpha_K\rho_K\left(H_K + \frac{V_K^2}{2}\right) - A\alpha_K\frac{\partial P}{\partial t} + \frac{\partial}{\partial z}A\alpha_K\rho_K\left(H_K + \frac{V_K^2}{2}\right) = AQ_{iK} + \chi_h Q_{WK} + A\alpha_K\rho_K V_K g_Z$$

Interfacial relations

$$\sum_K \Gamma_{iK} = 0 \qquad \sum_K I_{iK} = 0 \qquad \sum_K Q_{iK} = 0$$

Interfacial energy transfers

$$Q_{iK} = q_{iK} + \Gamma_{iK}\left(H_K + \frac{V_i^2}{2}\right)$$

q_{iK} is the interface to phase K heat flux.

$\Gamma_{iK}\left(H_K + \frac{V_i^2}{2}\right)$ is the energy transfer due to mass transfer.

Interfacial momentum transfers

$$I_{iK} = \tau_{iK} - p_i\frac{\partial \alpha_K}{\partial z} + \varepsilon_K A_m - \Gamma_{iK}V_i$$

τ_{iK} interfacial friction term = stationary part of interfacial forces

$p_i\frac{\partial \alpha_K}{\partial z}$ is due to the non-homogeneous transverse pressure field. It controls the propagation of void fraction waves.
The p_i expression can be analytically derived in case of horizontal stratified flow (assuming a hydrostatic transverse pressure gradient).
For non-stratified flows, the p_i term does not play an important role and the expression of p_i is chosen to provide the hyperbolicity of the system.

A_m $= \beta\alpha(1-\alpha)\rho_m\left[\frac{\partial V_G}{\partial t} - \frac{\partial V_L}{\partial t} + V_G\frac{\partial V_G}{\partial z} - V_L\frac{\partial V_L}{\partial z}\right]$
is the added mass term which controls the speed of sound of the model (ε_L=+1, ε_L=-1).

$\Gamma_{iK}V_{iK}$ is the momentum transfer due to mass transfer.

CATHARE

ASSESSMENT
CATHARE QUALIFICATION TEST MATRIX (1)

Main Phenomena *(CATHARE module)*	EXPERIMENT	Mech. Transf.	Interf. Heat Transf.	Wall Heat Flux	Component
Critical flowrate *0-D, 1-D modules*	SMD long nozzle	•	•		Break
	SMD short nozzle	•	•		Break
	BETHSY nozzle	•	•		Break
	MARVIKEN 14. 24	•	•		Break
	REBECCA diaphragm	•	•		Break
	REBECCA orifice	•	•		Break
Interfacial friction Flow regimes *1-D module*	CANON vertical tube	•			Break
	CANON vertical rod bundle	•			Core
	TAPIOCA	•			Break
	PERICLES boil up	•		•	Core
	BETHSY core	•		•	Core
	PATRICIA SG2	•		•	SG secondary
	ECTHOR intermediate leg	•			Intermediate Leg
	SMD horizontal (90, 135)	•			
	MHYRESA droplet	•		•	Hot Leg
	MHYRESA entrainment	•			Hot Leg
Wall friction *1-D module*	MD air-water	•			
	CISE	•			
	Collier	•			
CCFL *0-D, 1-D modules*	MHYRESA CCF B118	•			Hot Leg
	MHYRESA CCF R350	•			Hot Leg
	ECTHOR hot leg	•			Hot Leg
	MHYRESA PSC	•			Core
	MHYRESA SG tube	•			SG tube
	HANNOVER	•			Core
	UPTF BC 11-26c	•			Hot Leg
Reflooding *1-D module*	PERICLES reflooding	•	•	•	Core
	ERSEC rod bundle	•	•	•	Core
	ROSCO	•	•	•	Core
	REWET II	•	•	•	Core - VVER
Wall flux *1-D module*	OMEGA rod bundle	•	•	•	Core
	COSI	•	•	•	
	PATRICIA SG1	•	•	•	SG tube
	COTURNE	•	•	•	SG tube
	MIT	•	•	•	
	TOSHIBA	•	•	•	
	KIT	•	•	•	
	FLECHT SG	•	•	•	SG

ASSESSMENT
CATHARE QUALIFICATION TEST MATRIX (2)

Main Phenomena *(CATHARE module)*	EXPERIMENT	Mech. Transf.	Interf. Heat Transf.	Wall Heat Flux	Component
Rewetting Film boiling	WINFRITH (hot patch) INEL rewetting tests TPTF	• • •	• • •	• • •	Core Core Core
Condensation *1-D module*	COSI (ECC, Accu, NC) COSI tee		• •		ECC ECC
Fuel model *1-D module*	REBEKA EDGAR			• •	Fuel Fuel
Downco refilling *1-D module*	UPTF (5a, 5b, Z3E)	•	•		Downcomer
Phase separation *Tee and sink*	SMD tee INEL MHYRESA tee	• • •			Break Break Break
Lower plenum voiding *0-D module*	PIERO	•			Lower Plenum
Upper plenum deentrainment *0-D module*	UPTF 10C	•			Upper Plenum
Pump *0-D module*	EVA 0-D	•	•	•	Pump
Pressurizer *0-D module*	DAMPIERRE	•	•	•	Pressurizer
SG secondary side *1-D module*	PALUEL	•	•	•	SG
Downco refilling *3-D module*	UPTF (6, 7, Z3E)	•	•		Downcomer
Core uncovery *3-D module*	PERICLES 2-D boil up PERICLES 2-D reflooding	• •	•	• •	Core Core
Upper plenum *3-D module*	UPTF 10C (CCFL UTP)	•			Upper Plenum
Lower plenum *3-D module*	PIERO	•			Lower Plenum

ASSESSMENT
VERIFICATION ON INTEGRAL TESTS

Several integral tests are calculated for:

- Validating the general coherency of the models
- Testing the code capability to represent system effects
- Verifying the description of scaling effects
- Drawing attention to points which need further physical investigations

System test facilities for CATHARE verification

LOOP	VERT. SCALE	VOLUME SCALE	POWER	PRESSURE MPa	LOOB NB	CORE
LOFT	1/2	1/48	100%	16	2	Nuclear
LSTF	1/1	1/48	14%	16	2	Electrical
BETHSY	1/1	1/100	10%	16	3	Electrical
LOBI	1/1	1/700	100%	16	3	Electrical
PACTEL	1/1	1/305		8	3	Electrical

Selected tests for the assessment of CATHARE 2 Version 2.5 Revision 6.1

LB LOCA		
	LOFT L2-5	LBLOCA (0-D/1-D and 3-D modelling of the vessel)
	LOFT LP02-6	LBLOCA (0-D/1-D and 3-D modelling of the vessel)
	BETHSY 6.7c	Reflooding, base case
INTERMEDIATE BREAK		
	BETHSY 4.2b*	1.6" Break, Lower Plenum
	BETHSY 9.1b	2" Break, Cold Leg, without HPSI
	BETHSY 8.1	3" Break, Cold Leg, delayed MCP trip
	BETHSY 7.3b	3" Break, Hot Leg, without HPSI, nitrogen injection
	BETHSY 6.2TC	6" Break, Cold Leg, Counterpart Test
	LSTF SBCL 21	6% Break, Cold Leg
	LSTF SBCL 09	10" Break, Cold Leg
OTHER TRANSIENTS		
	BETHSY 6.8	4" Break, RHR Line, RHR system in operation
	BETHSY 4.3b	SGTR, 6 tubes
	BETHSY 4.1aTC	Natural Circulation, Counterpart Test
	PACTEL ISP33*	Natural Circulation, VVER
	BETHSY 5.2e	Total Loss of Feedwater
	BETHSY 6.9c	Loss of RHR (saturated), (1-D and 3-D modelling of the core)
	BETHSY 6.9d	Loss of RHR (non-condensable gases)
	LOBI BT 12*	Steam Line Break
	LSTF TR 03	Total Loss of Electrical Power

*** Independant assessment (Pisa university - Italy, LUT - Finland)**

APPLICATION OF CATHARE TO CONTAINMENT

Main objectives

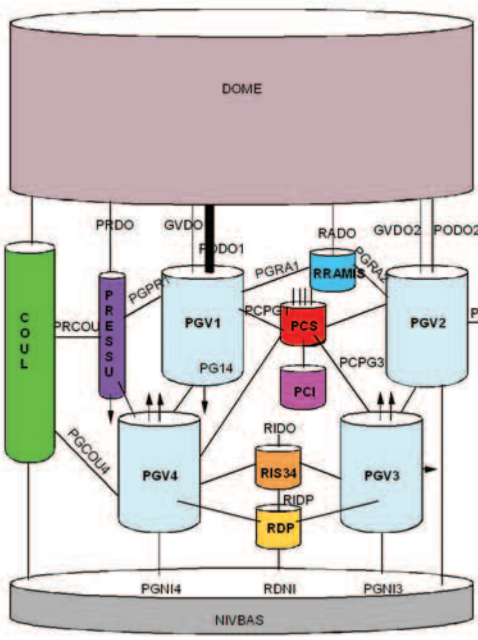
- ❖ Calculations of thermal-hydraulics for the containment design basis accident (large break LOCA or steam line break)
- ❖ Advantages:
    - to optimize the margins for the containment pressure
    - to calculate the reactor and the containment thermal-hydraulics with a single code (explicit coupled calculation between reactor thermal-hydraulics and containment thermal-hydraulics is possible)
    - to model the containment with one or several 0-D modules (dome, bunkers)

Features

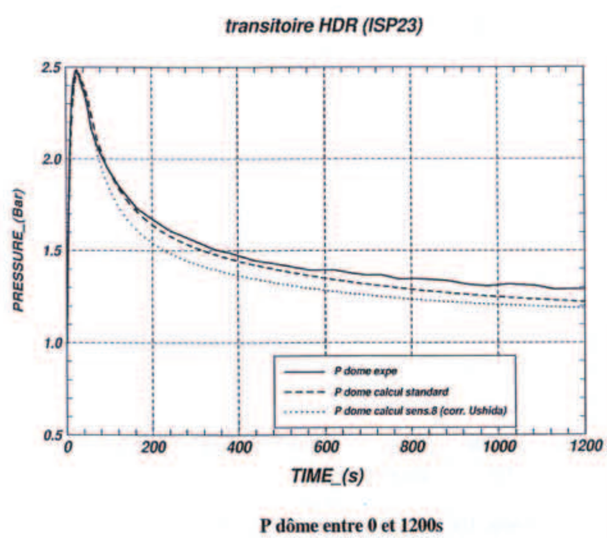
- ❖ Development of specific sub-modules:
    - mass and energy distribution at the break
    - operation of safeguard system with sump recirculation

Validation

- ❖ On separate effect tests : DEHBI, COPAIN
- ❖ On integral test facilities : CVTR (tests 3 and 5), HDR (ISP23)



Modelling of a reactor containment with 0-D modules



ISP23 calculations
Evolution of the dome pressure

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SENSITIVITY AND UNCERTAINTY ANALYSIS FOR CATHARE

Two tools have been developed by the CATHARE team:

- ❖ **ASM** (Adjoint Sensitivity Method)
  - goal
    - calculation of local sensitivities of responses R with respect to the parameter α: $\frac{\partial R}{\partial \alpha}$
  - example
    - response = void fraction at a given time and for a given elevation
    - parameter = multiplicative parameter of interfacial friction
  - developed for the 1-D module of CATHARE, with or without walls
  - systematic validation of numerous tests via recalculation of the sensitivity by finite differences

- ❖ **CIRCÉ** (Calcul des Incertitudes Relatives aux Corrélations Elémentaires)
  - goal
    - estimation of the bias and the standard deviation of the uncertain parameters associated with the physical models of CATHARE
  - it consists of a statistical analysis of the SET experiments. It uses the sensitivities calculated by ASM for the 1-D module and the finite differences for the 0-D module.
  - systematic validation namely via envelop calculations
  - examples of uncertainties determined with CIRCÉ
    - heat exchange transfers in the core, in the dry zone, during the refill phase of a LB LOCA (TPTF experiment)
    - physical phenomena involved in critical flow experiments (Super Moby Dick, BETHSY nozzle, REBECCA experiments): liquid interface heat transfer, wall liquid friction, interfacial friction, ...

Further developments

- ❖ Development of a complete methodology for uncertainty and sensitivity analysis, in the frame of the international program BEMUSE (Best-Estimate Methods – Uncertainty and Sensitivity Evaluation):
  - combination of the uncertainties by a fully probabilistic method:
    - all the uncertain parameters are varied simultaneously
  - analysis of the results:
    - use of Wilkes formula
    - CATHARE is replaced by several types of response surfaces. For each of them, calculation of α-fractiles by Monte-Carlo runs
- ❖ Development of a specific method for the uncertainties involved in the 3-D module of CATHARE

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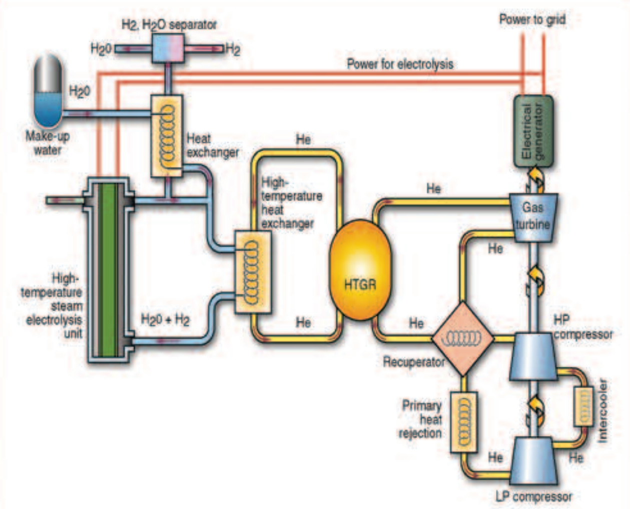
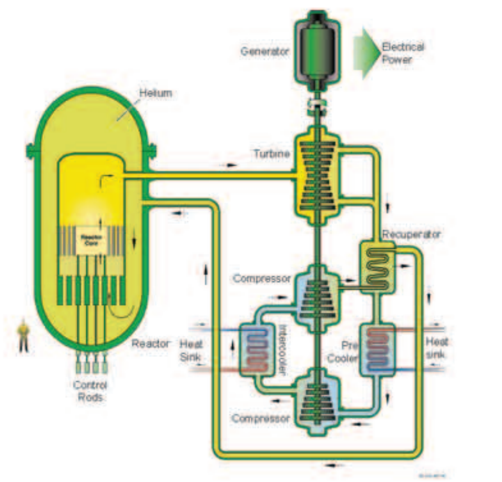
APPLICATION TO GAS COOLED REACTORS (1)

Context

❖ As part of the International forum GENIV, **two innovative concepts** of Gas Cooled Reactor (GCR) are investigated:



• the **Very High Temperature Reactor** (VHTR)



• the **Gas cooled Fast Reactor** (GFR)

Use of CATHARE

❖ CATHARE is used for:
- **design studies** (parameter calculations)
- **system analysis** (nominal, incident and accident transients)

Range of applications

❖ Studies are carried out on several gas cooled reactors:
- modular High Temperature Gas Reactor (HTGR)
- Very High Temperature (VHTR)
- Next Generation Power Plant (NGNP)
- Gas cooled Fast Reactor (GFR), single or multi-loops
- EDTR

CATHARE specific developments and adaptations

❖ O-D turbo-machine module with specific characteristic functions for gas turbines and compressors which may be coupled to a single shaft

❖ Neutron kinetics feedback model specific to the GCR

❖ Specific core thermal modelling with a simplified 2-D conduction calculation

❖ Specific heat exchangers modelling (case of crossed flows)

❖ Simplification of the 6-equation model for gas single phase calculation

Example of studies

❖ Several accident transients have already been calculated:
- loss of electrical load with and without turbo-machine trip
- 10" cold break
- 10" cold break combined with a tube rupture of the shutdown sooling system (water ingress)
- turbine failure (compete/partial plugging or « true » deblading)
- loss of feedwater on secondary side (intercooler and precooler)
- different decay heat removal systems simulations for a GFR (nitrogen injection, natural convection, ...)

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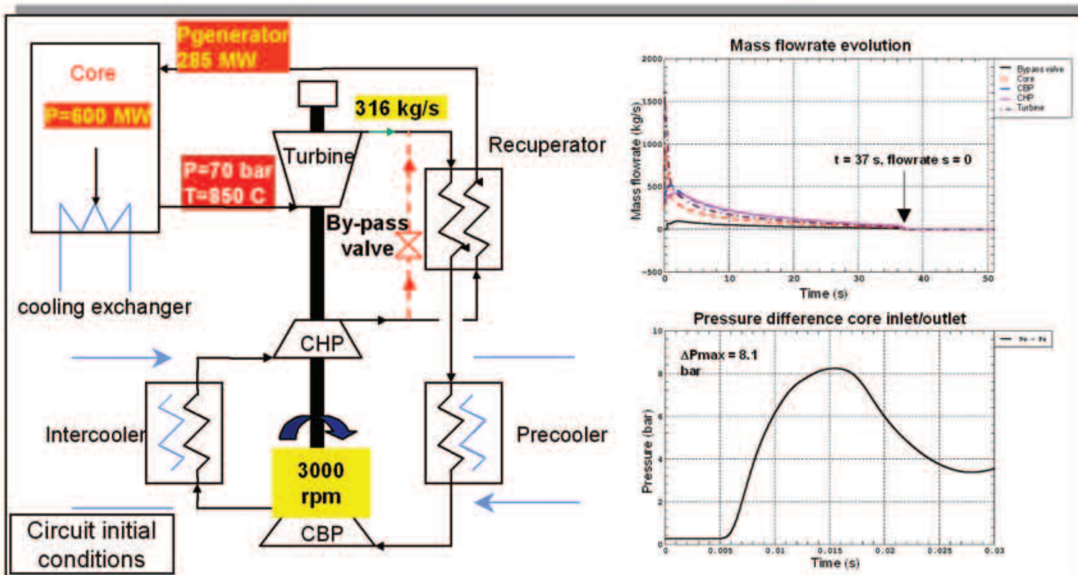
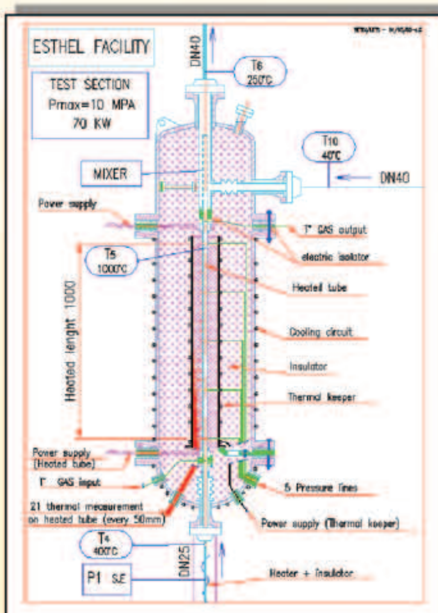
APPLICATION TO GAS COOLED REACTORS (2)



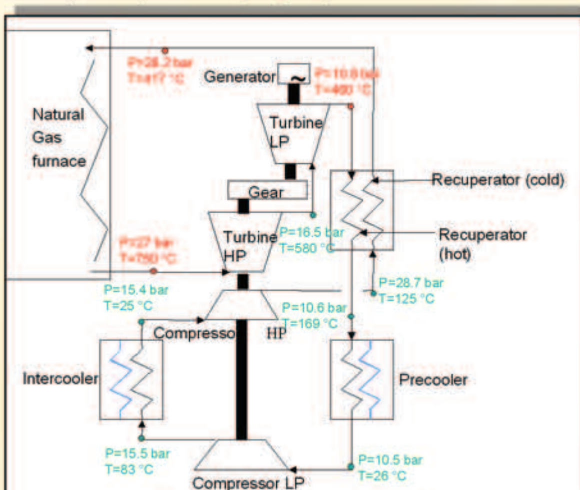
Turbine deblading transient CATHARE results

Experimental validation of CATHARE applied to GCR

- Validation on ***Separate Effect Tests*** to get the adequate heat transfer and pressure drop coefficients for all the flow regimes (in the core and in the heat exchangers)
  - **ESTHEL, ESTHAIR** (CEA Grenoble)
- Validation on ***Component Tests*** (recuperator, turbomachine, …)
  - **HELITE** (CEA Cadarache)
- Validation on ***System Test Facilities*** to take into account all the dynamic interactions during transient situations, including regulations
  - **EVO** (Helium turbine plant) (Germany)
  - **PBMM** (**P**ebble **B**ed **M**icro **M**odel) (South Africa)
  - **HTR-10** (China), **HTTR** (Japan), …



ESTHEL facility



Schematic view of EVO


EVO

Further developments

- Coupling with: 3-D kinetics, CFD code, Thermochemical process
- 1-D description of all the elements of turbomachinery for steady and unsteady regimes

International collaborations

- European partners, DOE/Generation IV, JNC/JAERI, Minatom

CATHARE

ICARE/CATHARE
A computer system code for analysis of severe accidents in LWRs

Context

- The ICARE/CATHARE system code is being developed by the IRSN within the framework of PWR safety analysis studies. It is the result of a coupling of the IRSN mechanistic severe accident code ICARE2 with CATHARE 2 thermal-hydraulics modules (1-D and 3-D).

Objectives

- The development of the ICARE/CATHARE code meets three main objectives:
  - to provide a pertinent tool for the calculation of the whole severe accidental sequence in a LWR
  - to provide analytical support to experimental programs (PHEBUS FP, PHEBUS ST, ...)
  - to make a synthesis, within a coherent framework, of all the phenomenological knowledge on core degradation

In this respect, the code is used at the IRSN in PSA level 2 studies for the analysis of PWR accidental sequences.

Principle of the coupling

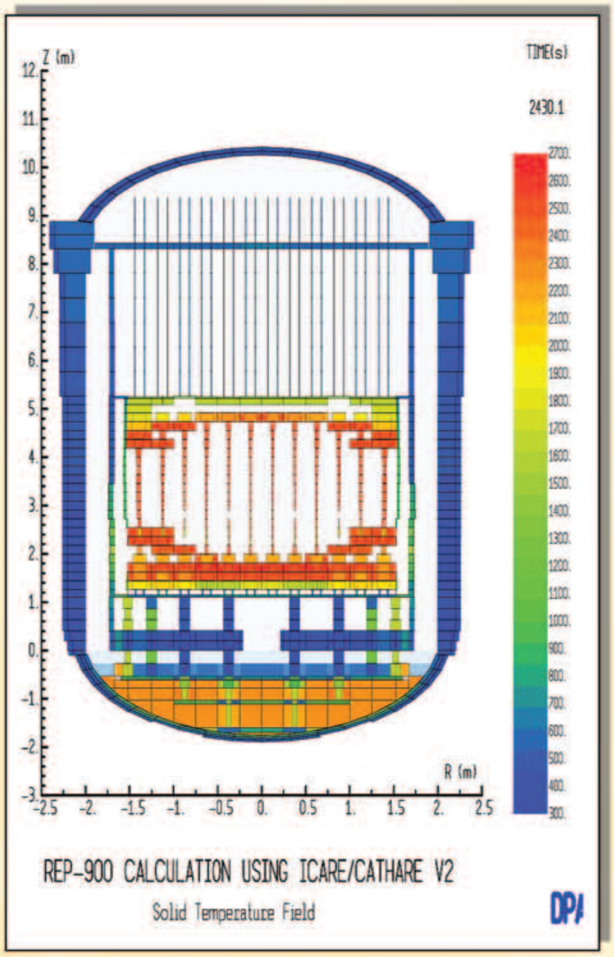
- In the implicit coupling between the two codes, ICARE2 plays the role of a new kind of wall describing the thermal, chemical and mechanical behaviour of fuel rods and structures in the reactor vessel. CATHARE 2 calculates the behaviour of structures in the other elements of the circuit, the circuit thermal-hydraulics and manages the time step.
- The data exchange between the two codes is performed through an interface zone.

ICARE/CATHARE project progress

- The first version, ICARE/CATHARE V1, released in July 1999, was based on the coupling of ICARE2 with CATHARE 2 V1.3L and therefore was limited to one dimensional calculations.
- The current version, ICARE/CATHARE V2, based on the latest verions of the two codes, ICARE2 V3 mod3.1 and CATHARE 2 V2.5, allows 2-D aspects to be considered in the vessel (present ICARE2 models are 2-D).
- In the final version, ICARE/CATHARE V3, ICARE2 modeles will be extended to allow a 3-D modelling of the vessel. Moreover a general reflooding model , able to deal with any geometry (intact or degraded rods, debris beds) will be available.

ICARE/CATHARE validation

- The validation matrix consists of thermal-hydraulic non-regression tests (taking advantage of the CATHARE 2 validation matrix), separate effect tests (chemical interactions, mechanics, quenching, ...), early phase and late phase degradation tests and tests with hydraulics loops. It also includes a detailed analysis of the TMI-2 accident.



CATHARE

IRSN

SCAR project: simulator SIPA2 with CATHARE 2 V2.5

The standard CATHARE 2 version V2.5 is now used in the training and engineering french simulator SIPA2. This was the goal of the SCAR project ending in 2004 (CEA, EDF, IRSN).

Main features for a 900 MW PWR configuration (CP1)

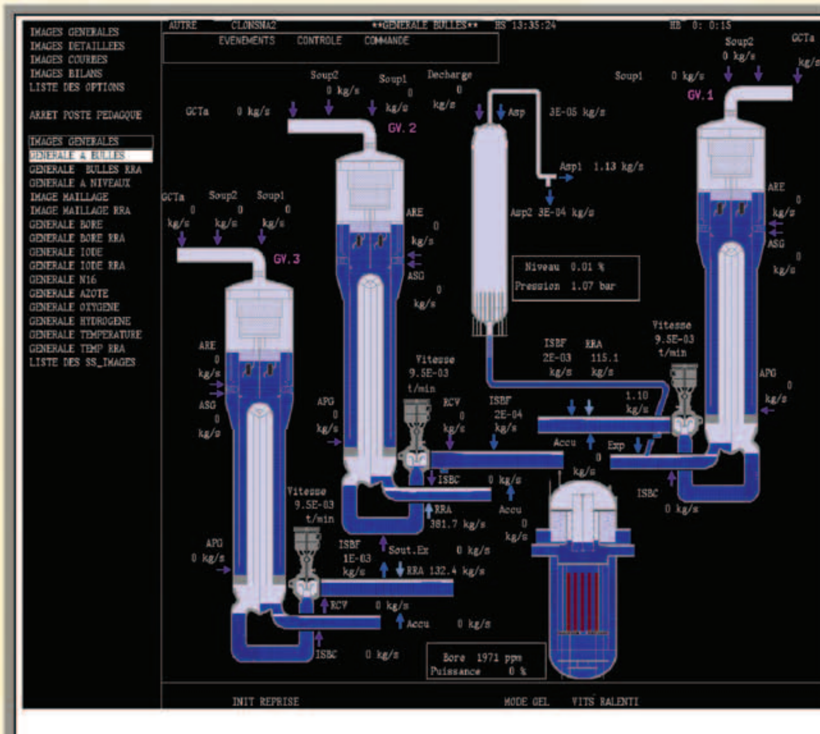
- The primary circuit, the secondary circuits and the Residual Heating Removal system (RHR) are calculated by CATHARE, « plugged » as an external library.
- SIPA inter-operability rules describe the format of the data exchanged by the different systems. The auxiliary systems are linked to the vessel through connecting points calling CATHARE standard interfaces.
- Scope of simulation:
  - it goes from the nominal power to the cold shutdown and mid-loop states. The user can expand the standard library of initial states with his own initial states.
- Calculation of non-condensable gases:
  - nitrogen in the accumulators and air (O_2 + N_2 + H_2) when the vessel is open (vents, pressurizer or SG manholes) can be calculated.
- Modelling capabilities:
  - it includes actuators (control valves, check valves, safety valves, manholes of SG and PZR, ...), sensors, nozzles, ...
- Failures can be modelled on actuators or pumps. The cavitation model allows to take into account the pump characteristics degradation.
- Pressurizer spray lines and accumulators are meshed and calculated by CATHARE.
- Radio-active and chemical products transports (boron, N_{16}, I_{131}) are calculated.

Validation on a wide range of transients

- 10 Regulatory Guide transients, 4 comparisons with French PWR transients, 7 accident transients at nominal power, 4 accident transients in cold shutdown states.

Performance

- Real time in most transients with a synchronism time of 100 ms. This goal has been obtained by improving CATHARE reliability on 50 transients, decreasing the elementary calculation time and using the CATHARE parallel version (Open MP).



Mid-loop state for primary circuit

NEPTUNE (1)
A New Software Platform for Advanced Nuclear Thermal-hydraulics

From CATHARE 2 V2.5 to NEPTUNE

NEPTUNE, a thermalhydraulic software platform will include all capabilities of CATHARE

- New **models** (multi-field, transport of interfacial area, turbulence modelling, ...)
- A **CFD module** to allow local zoom in some components of the circuit
- New numerical features (body fitted meshing, parallelism, ...)
- A new **architecture** allowing multi-scale coupling and easy coupling with neutronics, fuel thermo-mechanics

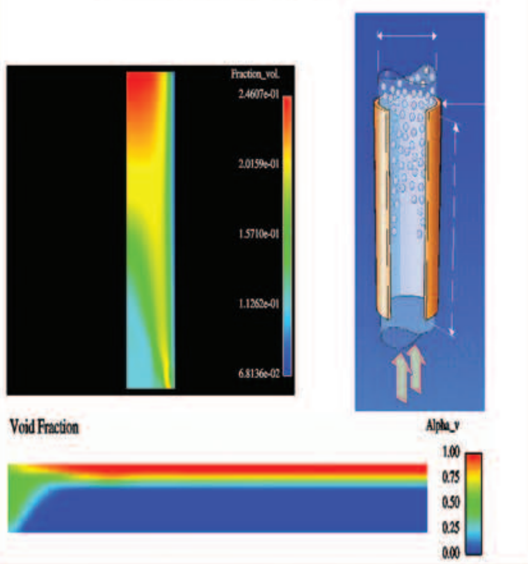
The NEPTUNE project

- To prepare a **new generation** (2010) of industrial two-phase flow codes covering **the whole range of modelling scales**
- To build a new software platform allowing **easy multi-scale and multi-disciplinary coupling** in a shared environment

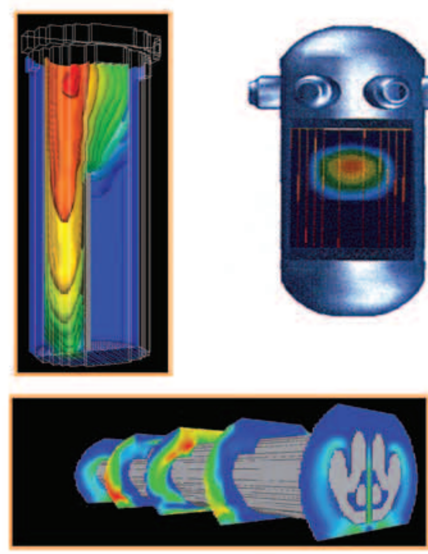
*EDF and CEA launched in 2001 a new joint development program for nuclear reactors advanced simulation tools. **NEPTUNE** covers the area of **two-phase flow thermal hydraulics**. The whole project is built on a deep analysis of the **industrial needs.***

3-D modelling and computing scales

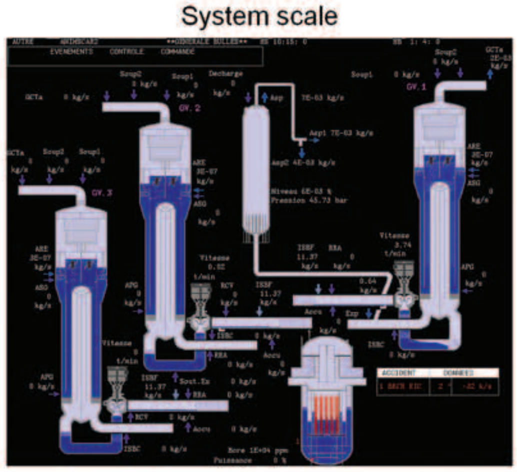
3-D local scale (open medium)



3-D component scale (porous medium)



System scale



NEPTUNE (2)
A New Software Platform for Advanced Nuclear Thermal-hydraulics

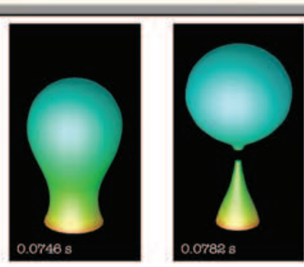
An advanced software architecture

- A **component architecture** with shared modules, compatible with the user-friendly **SALOME platform,** shared with the other disciplines, including **parallelism**

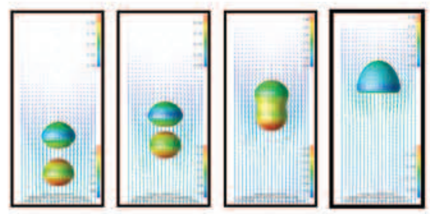
The R&D effort

Physical R&D for new two-phase flow models, **Numerical R&D** for precise and robust solvers, **Experimental programs** for validated tools:

- Advanced **two-fluid models and multi-field formulations** for **all flow regimes**, for **open & porous media,** development and use of **DNS** techniques



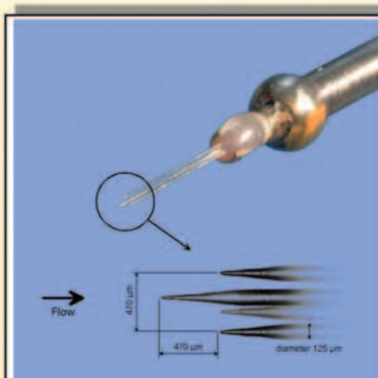
DNS for bubble growing and detachment



DNS for bubble coalescence

- **Optimization** of fully unstructured 3-D finite volume solvers, development of **new TH/TH coupling methods** for industrial applications (1-D/3-D, 1 fluid/2 fluid, local/porous), development of new numerical methods (Finite Volume Element, 2-phase 2-pressure solvers), **CPU optimization** (multi-grid, domain decomposition)
- Development of **advanced instrumentation,** physical validation and **qualification for industrial applications**

Flow in SG tube bend



Four sensor optical probe

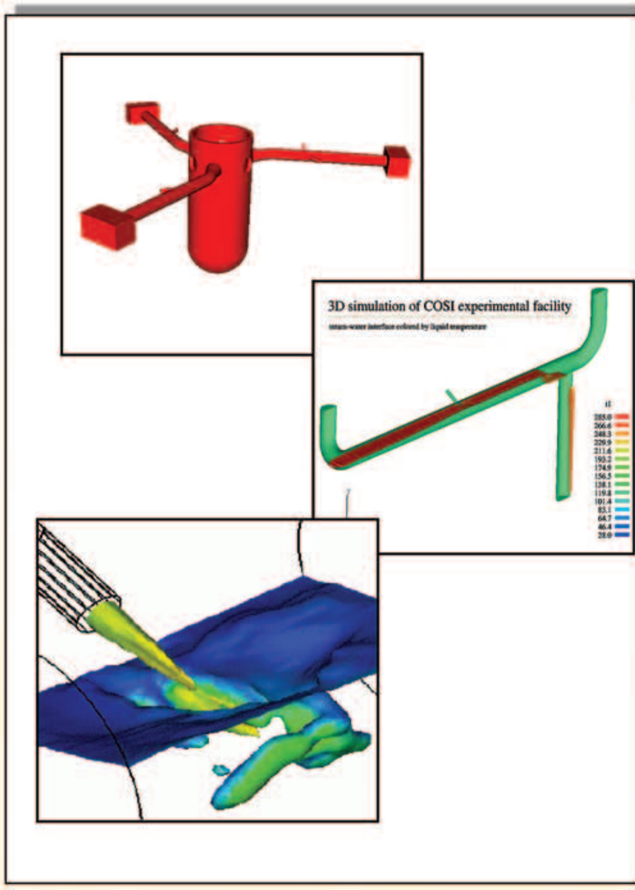
X-Rays tomography

Some industrial applications

- **Local scale** (two-phase CFD) : pressurized Thermal Shock, CHF local prediction, mixing grids, separators…
- **Component scale** : cores, steam generators, condensers, tubular heat exchangers…
- **System scale** : reactor analysis under operating and accidental conditions, fast transients…
- **TH/TH Multi-scale coupling** : PTS analysis (local scale/system scale)…
- **Multi-disciplinary coupling** : SLB, LOCA analysis (system/component/neutronics/fuel)…

NEPTUNE

NEPTUNE (3)
A New Software Platform for Advanced Nuclear Thermal-hydraulics



NEPTUNE - CFD in open medium & multi-scale coupling

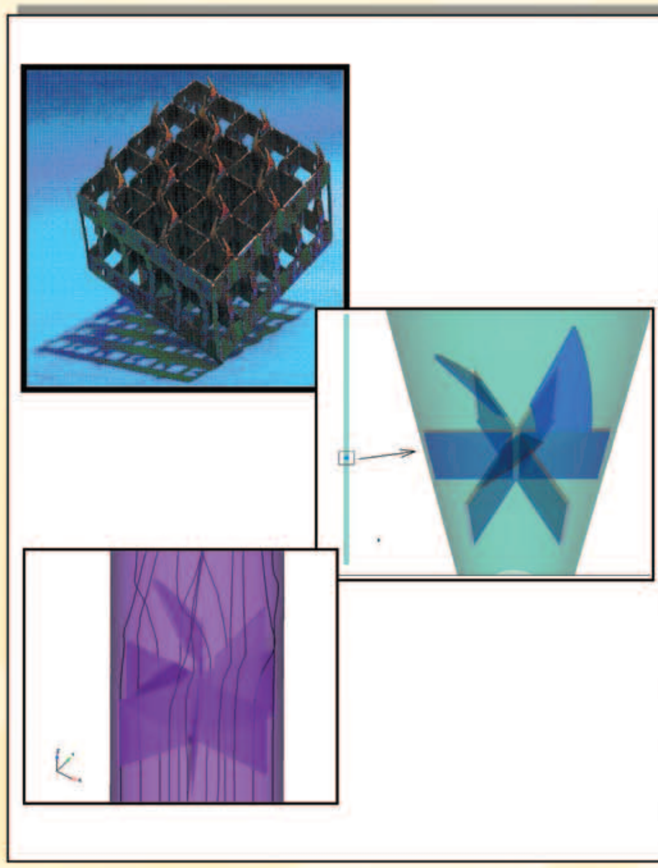
Application to ***Pressurized Thermal Shock*** Investigations

- In some accidental scenarios, cold water (safety injection) is injected directly into the cold leg which can be partially uncovered (liquid layer and steam), leading to a two-phase Pressurized Thermal Shock (PTS) configuration.
- Coupled with a system scale calculation (CATHARE), NEPTUNE CFD module provides us with the time-dependent 3D local field of the liquid temperature on the pressure vessel, which is themain parameter to be determined.
- **NEPTUNE** CFD V1.0 (2004) handles both disperse and separate phases flows. It includes specific closure laws to deal with direct contact condensation, interfacial heat and momentum transfers, turbulence in the jet impact area and in the stratified region.
- **NEPTUNE** CFD validation is being carried out against experimental data : integral facilities as COSI, the anticipated NURESIM new experiment and also separate effect experiments to validate some parts of the modelling.

NEPTUNE – Two-phase CFD in complex geometries

Application to ***spacer grids*** calculations

- Fuel performance is one of the major issues for the competitiveness of nuclear power plants. Its assessment requires a very precise prediction of DNB (Departure from Nucleate Boiling) and Dry-Out in PWR and BWR cores.
- The geometry of the spacers has a very important effect on the occurrence of CHF (Critical Heat Flux). Powerful CFD tools are necessary to calculate both single-phase and two-phase flows in such geometries. They will help us to develop precise CHF predictors based on local thermal-hydraulics parameters.
- **NEPTUNE** CFD V1.0 handles two-phase flows in very complex geometries.
- **NEPTUNE** is parallel and runs on every kind of platform, from small Linux clusters to massively parallel super-computers such as the new French CCRT.
- **NEPTUNE** validation on complex geometries is being carried out against experimental data, such as the DEBORA and AGATE tests.



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